Marine Aerosols: Hygroscopocity and Aerosol-Cloud Relationships

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LONG-TERM GOALS

The long-term goal of this project is to predict the radiative properties of the marine atmosphere based on aerosol and cloud properties.

OBJECTIVES

The objective of the project is to improve our understanding of the role of aerosols in the Marine Boundary Layer and our ability to simulate marine stratocumulus clouds as a function of aerosol properties and the large-scale meterology.

APPROACH

The proposed research consists of laboratory, aircraft experiment, and modeling studies that address the hygroscopic properties of aerosols and aerosol-cloud relationships in marine stratocumulus (MSc) clouds. A CIRPAS Twin Otter field experiment took place in July-August 2011 over the eastern Pacific Ocean off the coast of Monterey, CA. That experiment addressed the response of MSc to aerosol perturbations, in collaboration with Professors Bruce Albrecht of the University of Miami, Armin Sorooshian of the University of Arizona, and Lynn Russell of UCSD. (Since field experiments

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generally need an acronym, we designated this experiment as the Eastern Pacific Emitted Aerosol Cloud Experiment, E-PEACE.)

We will carry out further development and evaluation of aerosol-cloud modeling in the marine boundary layer. Much work has been carried out directed at understanding the response of marine stratocumulus to perturbations in marine aerosols, including large eddy simulation (LES) and field measurements, the latter including Twin Otter missions such as MASE I and MASE II and those involving other platforms such as DYCOMS and VOCALS, going back to the original MAST campaign. The MAST mission was the first to systematically probe the cloud properties in ship tracks, which have continued to serve as a well-defined example of marine aerosol-cloud perturbations. The aircraft payload has advanced considerably beyond the original MAST experiment, now comprising an aerosol mass spectrometer, CCN spectrometer, soot photometer, photoacoustic spectrometer, and phase doppler interferometer. It is now possible to fully characterize the aerosol physical, chemical, and optical properties. Important theoretical work remains to be done to fully understand aerosol-cloud relationships in marine stratocumulus. In addition, most of the cloud microphysical modeling done independently or in conjunction with field missions has yet to be reflected in atmospheric models. We will carry out microphysical modeling and LES studies with the goal of deriving treatments appropriate for atmospheric models. The July-August 2011 Twin Otter field experiment was focused on marine aerosol-cloud measurements. These will involve cloud microphysics closure, which will assess the extent to which model prediction of cloud droplet number concentration, drizzle, and cloud thickness agree with those measured.

Since the experiment just ended a few weeks ago, results will be given in next year’s annual report. Table 1 lists the flights and instrument performances. Table 2 lists the aircraft payload. Figure 1 shows views of two ships whose exhaust was used as the basis for MSc aerosol perturbation.

WORK COMPLETED

Theoretical basis for convective invigoration due to increased aerosol concentration

The potential effects of increased aerosol loading on the development of deep convective clouds and resulting precipitation amounts are studied by employing the Weather Research and Forecasting (WRF) model as a detailed high-resolution cloud resolving model (CRM) with both detailed bulk and bin microphysics schemes. The bulk microphysics scheme incorporates a physically based parameterization of cloud droplet activation as well as homogeneous and heterogeneous freezing in order to explicitly resolve the possible aerosol-induced effects on the cloud microphysics. These parameterizations allow one to segregate the effects of an increase in the aerosol number concentration

into enhanced cloud condensation nuclei (CCN) and/or ice nuclei (IN) concentrations using bulk microphysics. The bin microphysics scheme, with its explicit calculations of cloud particle collisions, is shown to better predict cumulative precipitation. Increases in the CCN number concentration may not have a monotonic influence on the cumulative precipitation resulting from deep convective clouds. We demonstrate that the aerosol-induced effect is controlled by the balance between latent heating and the increase in condensed water aloft, each having opposing effects on buoyancy. It is also shown that under polluted conditions and in relatively dry environments, increases in the CCN number concentration reduce the cumulative precipitation due to the competition between the sedimentation and evaporation/sublimation timescales. The effect of an increase in the IN number concentration on the dynamics of deep convective clouds is small, but may act to suppress precipitation. It is also shown that even in the presence of a decrease in the domain-averaged cumulative precipitation, an increase in the precipitation variance, or in other words, and increase in rainfall intensity, may be expected in more polluted environments, especially in most environments.

A significant difference exists between the predictions based on the bin and bulk microphysics schemes of precipitation and the influence of aerosol perturbations on updraft velocity within the convective core. The bulk microphysics scheme shows little change in the latent heating rates due to an increase in the CCN number concentration, while the bin microphysics scheme demonstrates significant increases in the latent heating aloft with increasing CCN number concentration. This suggests that even a detailed two-bulk microphysics scheme, coupled to a detailed activation scheme, may not be sufficient to predict small changes that result from perturbations in aerosol loading.

A continuous spectral aerosol-droplet microphysics model

A two-dimensional (2-D) continuous spectral aerosol-droplet microphysics model has been developed and implemented into the Weather Research and Forecasting (WRF) model for large-eddy simulations (LES) of warm marine stratocumulus clouds. Activation and regeneration of aerosols are treated explicitly in the calculation of condensation/evaporation. The model includes a 2-D spectrum that encompasses wet aerosol particles (i.e. haze droplets), cloud droplets, and drizzle droplets in a continuous and consistent manner and allows for the explicit tracking of aerosol size within cloud droplets due to collision-coalescence. The system of differential equations describing condensation/evaporation (i.e. mass conservation and energy conservation) is solved simultaneously within each grid cell. The model is demonstrated by simulating a marine stratocumulus deck for two different aerosol loadings (100 and 500 cm^{-3}), and comparison with the more traditional microphysics modeling approaches (both 1-D bin and bulk schemes) is evaluated.

A Comprehensive Numerical Study of Aerosol-Cloud-Precipitation Interactions in Marine Stratocumulus

Three-dimensional large-eddy simulations (LES) with detailed bin-resolved microphysics are performed to explore the diurnal variation of marine stratocumulus (MSc) clouds under clean and polluted conditions. The sensitivity of the aerosol-cloud-precipitation interactions to variation of sea surface temperature, free tropospheric humidity, large-scale divergence rate, and wind speed is assessed. The comprehensive set of simulations corroborates previous studies that (1) with moderate/heavy drizzle, an increase in aerosol leads to an increase in cloud thickness; and (2) with non/light drizzle, an increase in aerosol results in a thinner cloud, due to the pronounced effect on entrainment. It is shown that for higher SST, stronger large-scale divergence, drier free troposphere, or lower wind speed, the cloud thins and precipitation decreases. The sign and magnitude of the Twomey effect, droplet dispersion effect, cloud thickness effect, and cloud optical depth susceptibility to aerosol to aerosol perturbations (i.e., change in cloud optical depth to change in aerosol number concentration) are evaluated by LES experiments and compared with analytical formulations. The Twomey effect emerges as dominant in total cloud optical depth susceptibility to aerosol perturbations. The dispersion effect, that of aerosol perturbations on the cloud droplet size spectrum, is positive (i. e., increase in aerosol leads to spectral narrowing) and accounts for 3% to 10% of the total cloud optical depth susceptibility at nighttime, with greater influence in heavier drizzling clouds. The cloud thickness effect is negative (i.e., increase in aerosol leads to thinner cloud) for non/light drizzling cloud and positive for a moderate/heavy drizzling clouds; the cloud thickness effect contributes 5% to 22% of the nighttime total cloud susceptibility. Overall, the total cloud optical depth susceptibility ranges from ~0.28 to 0.53 at night; an increase in aerosol concentration enhances cloud optical depth, especially with heavier precipitation and in a more pristine environment. During the daytime, the range of magnitude for each effect is more variable owing to cloud thinning and decoupling. The good agreement between LES experiments and analytical formulations suggest that the latter may be useful in evaluations of the total cloud susceptibility. The ratio of the magnitude of the cloud thickness effect to that of the Twomey effect depends on cloud base height and cloud thickness in unperturbed (clean) clouds.

RESULTS

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E-PEACE Twin Otter Flight and Instrument Performance Summary Table **Last updated:** 9/1/11

General Flight Information						Aerosol Physics and Chemistry				Soot/Optical Props		Optical Particle Counters									CIRPAS Misc		
RF	Flight Date	Flight Time (UTC)	Mission Type	Flight PI	Coord	CVI	DMA*	AMS*	CCN*	SP2*	PASS3*	CPC1*	CPC2	CPC3	PCASP	CAPS	CDP	FSSP	PDI	CFMCW	MET	NAV	LWC
1	7/8/11	20:55	salt seeding; thin clouds	Armin	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	< 50%	OK	N/A	down	OK	OK	OK	OK
2	7/9/11	16:52 - 21:03	salt seeding; thick, wet clouds, already drizzling	Andrew	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	N/A	down	< 50%	OK	OK	OK
3	7/13/11	16:11	broken clouds, weak smoke plume, but visible in data	Armin*	ship	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	< 50%	down	OK	OK
4	7/14/11	16:06 - 20:05	decent clouds, continental + ship plumes	Andrew	ship	OK*	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK
5	7/15/11	16:06	container ship in addition to ours; broken clouds	Armin	ship	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK
6	7/16/11	16:04 - 20:16	2 cloud layers above ship, wider smoke plume	Andrew	ship	OK	OK	OK	N/A	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	down
7	7/17/11	16:07 - 20:09	no clouds, shallow inversion, dirtiest day so far	Armin + Jill*	ship	OK	> 50%	> 50%	N/A	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK
8	7/19/11	16:04? - 20:11	wet, but not drizzling clouds; high bases, ship track	Andrew	ship	OK*	OK	OK	down	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK
9	7/21/11	16:05	drizzling clouds, weak plume but should be visible in cloud	Armin*	ship	OK	OK	OK	OK	OK	down	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK
10	7/22/11	16:05 - 20:19	spotty drizzle, wet clouds; plume in and above cloud (maybe)	Andrew*	ship	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK	OK	OK
11	7/23/11	16:02	no drizzle, short Pt Sur plume; better cargo ship plume	Armin	ship	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
12	7/24/11	16:00 - 20:08	weak ship plume, high cloud bases, clear air sampling mostly	Andrew	-	OK	> 50%	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK	OK	OK
13	7/26/11	16:03	major ship track with several smaller ship influences; salt seeding	Armin*	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK	OK	OK
14	7/27/11	16:37 - 20:35	major ship track without influence of others, thick cloud	Andrew	-	OK	OK	> 50%	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK	OK	OK
15	7/28/11	17:55	thin clouds, not very wet; one major ship track with couple others	Armin	-	OK	< 50%	> 50%	OK	OK	OK	OK	OK	OK	OK	OK	N/A	OK	OK	OK	OK	OK	OK
16	7/29/11	16:37 - 20:43	wet, not drizzling clouds; high bases; ship track in cloud; salt seeding	Andrew	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	N/A	OK	OK	OK	OK	OK	OK
17	8/1/11	16:01	thin, high base cloud with weak but visible plume; soundings in and out of plume	Armin	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	N/A	OK	OK	OK	OK	OK	OK
18	8/2/11	15:59 - 20:04	2 ships; 2nd near wet, thick cloud, decent plume; sounding in and out (4 total); salt seeding	Andrew	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	N/A	OK	OK	OK	OK	OK	OK
19	8/3/11	16:04	good plume in cloud, thick, not very wet cloud, drizzle late in flight; salt seeding	Armin	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	N/A	OK	OK	OK	OK	OK	OK
20	8/4/11	15:59 - 19:58	plume in broken, cumulous-looking clouds; then long W-E leg with steps in alt	Andrew	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	N/A	OK	OK	OK	OK	OK	OK
21	8/5/11	17:06	long N-S leg with steps in alt and spirals; decent clouds with spotty drizzle	Armin	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	N/A	OK	OK	OK	OK	OK	OK
22	8/8/11	17:28 - 21:47	below cloud top and wheels-in statistics; to S; thin, not very wet clouds; 6 soundings	Andrew	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	N/A	OK	OK	OK	OK	OK	OK
23	8/9/11	16:36	same as yesterday: cloud top statistics; same type of clouds, slightly more polluted	Armin	-	OK	OK	OK	OK	OK	> 50%	OK	OK	OK	OK	OK	N/A	OK	OK	OK	OK	OK	OK
24	8/10/11	16:39 - 20:40	full ship plume workup; decent clouds, spotty drizzle late in flight; salt seeding	Andrew	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	N/A	OK	OK	OK	OK	OK	OK
25	8/11/11	16:23	race track ship plume workup, lot of below cloud legs; salt with BC	Armin	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK	OK	OK
26	8/12/11	16:31 - 20:32	cloud characterization across shipping lane, no specific ship; salt with BC	Andrew	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
27a	8/15/11	15:20	marathon: south to north sampling at 100' a couple miles off shore; no clouds	Armin + Andrew	-	N/A	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	N/A	N/A	OK	OK	OK
27b	8/15/11	20:01		Armin + Andrew	-	N/A	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	N/A	N/A	OK	OK	OK
27c	8/15/11	23:31		Armin + Andrew	-	N/A	OK	OK	OK	down	OK	OK	OK	OK	OK	OK	OK	OK	N/A	N/A	OK	OK	OK
28a	8/16/11	15:57	marathon 2: nearly same pattern as yesterday, but with clouds today	Armin + Andrew	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
28b	8/16/11	18:50		Armin + Andrew	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
28c	8/16/11	23:11 - 00:33		Armin + Andrew	-	OK	OK	OK	OK	down	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
29a	8/17/11	17:56	N to Santa Rosa with clouds, but with E-W gradients much further W (crossed ADIZ)	Armin + Andrew	-	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK
29b	8/17/11	21:34		Armin + Andrew	-	OK	OK	OK	OK	down	OK	OK	OK	OK	OK	OK	OK	OK	< 50%	OK	OK	OK	OK
30a	8/18/11	16:46	N to Santa Rosa with up-down gradients above the inversion layer; few cloud legs	Armin	-	OK	OK	OK	OK	OK	down	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK
30b	8/18/11	20:15		Armin	-	OK	OK	OK	OK	down	down	OK	OK	OK	OK	OK	OK	OK	down	OK	OK	OK	OK

	Coord. legend:
ship	Point Sur Research Vessel

	Status legend:
OK*	CVI "droplet shatter" event

	Instrument performance legend:
*	Instrument behind the CVI
OK	Instrument was on and functioning well during the entire flight
> 50%	Instrument was functioning for most of the flight (suffered some loss of data quantity/quality)
< 50%	Instrument was functioning for some time during flight (suffered major loss of data quantity/quality)
down	Instrument was not functioning, or there were other errors resulting in no good data for this flight
N/A	Instrument was not on board or not turned on during flight

Table 2.

E-PEACE Twin Otter Instrument Summary Table

Instrument description:		Measurement Description
CVI	Counterflow Virtual Impactor Inlet	Dried cloud droplets greater than 8 micron diameter
DMA	Differential mobility analyzer	Dry particle size distributions from 15 nm to 1 micron
AMS	Aerodyne aerosol mass spectrometer	Sub-micron, non-refractory size-resolved and bulk aerosol composition
CCN	Cloud condensation nuclei counter	Cloud condensation nuclei at various supersaturations
SP2	Soot Photometer	Refractory black carbon number and mass distributions with coating information
PASS3	Photoacoustic Spectrometer	Absorption and scattering coefficient of aerosol particles
CPC1	Condensation Particle Counter (>10nm)	Total aerosol number concentration
CPC2	Condensation Particle Counter (>10nm)	Total aerosol number concentration
CPC3	Ultrafine Condensation Particle Counter (>3nm)	Total aerosol number concentration
PCASP	Passive Cavity Aerosol Spectrometer Probe	Particle size distribution from 120 nm to 2.5 micron
CAPS	Cloud, Aerosol, and Precipitation Spectrometer (CASF + CASB + CIP)	Aerosol and cloud hydrometeor size distributions from 0.5 to 50 micron and precipitation size distributions from 25 to 1550 micron
CDP	Cloud Droplet Probe	Droplet size distributions from 2 to 50 micron
FSSP	Forward Scattering Spectrometer Probe	Droplet size distributions from 0.5 to 47 micron
PDI	Phase Doppler Interferometer	Droplet size distributions from 0.5 to 2000 micron with droplet velocities from -100 to 300 m/s
CFMCW	Frequency-Modulated Continuous-Wave 95 GHz Doppler Cloud Radar	Vertical microphysical and velocity structure of clouds
Met	Meteorology probes (T, RH, P)	Meteorology data
Nav	Navigational data system (C = C-MIGITS, N = NovaTel, T = TansVector)	Navigational data, such as GPS coordinates, altitude, heading, pitch angle, etc.
LWC	Gerber Liquid Water Content Probe	Cloud liquid water content

Figure 1. ***In E-PEACE the CIRPAS Twin Otter probed the perturbation in marine stratocumulus (MSc) properties from ingestion of ship exhaust. The upper panel shows the Moss Landing Marine Laboratory R/V Pt. Sur emitting well-characterized smoke from an on-board pair of Army battlefield smoke generators. The lower panel shows a tanker, the exhaust from which was tracked for several hours in the overlying MSc.***